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# The Assimilation of Contaminants from Suspended Sediment and Algae by the Zebra Mussel, *Dreissena polymorpha*

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## Abstract

Since their invasion into the Great Lakes, zebra mussels, *Dreissena polymorpha*, have increased the water clarity in Lake St. Clair and Lake Erie due to their extensive particle filtration. Because these particles contain sorbed contaminants, the potential for contaminant accumulation from both suspended sediment and algae were examined. Sediment or algae were dosed with selected radiolabeled polycyclic aromatic hydrocarbon congeners and/or hexachlorobiphenyl (HCBP). Assimilation efficiencies were measured and depended on food quality. Zebra mussels, 17 ± 2 mm long, assimilated 58.3 ± 13.5 % of the pyrene and 44.7 ± 5.8 % of the benzo(a)pyrene (BaP) from sediment particles with a particle clearance rate of 493 - 897 ml/ g tissue/ h. However, assimilation efficiencies were 91.7 ± 3.7 % for pyrene, 91.9 ± 1.4 % for BaP, 96.6 ± 1.4 % for chrysene, and 97.7 ± 0.5 % for HCBP from suspended algae. Algal particle clearance rates for the mussels ranged from 47 - 143 ml/ g tissue/ h. Thus, zebra mussels efficiently accumulated non-polar contaminants sorbed to algae, while a smaller fraction of the sediment-associated contaminant was bioavailable. Furthermore, the contaminants sorbed onto suspended sediment particles were quickly removed from the water and deposited as pseudofeces. The pseudofeces production was positively correlated with filtration rate and suspended particle concentrations. Published by Elsevier Science Ltd

## Introduction

Since their invasion into the Great Lakes, zebra mussels quickly settled on various hard substrates and are now found in large numbers, 500,000/m$^3$ (O'Neill and MacNeill 1989). Their density, combined with their high filtration rate (~ 1 L per day per mussel, Fisher *et al.* 1993) have resulted in increased water clarity in Lake St. Clair and Lake Erie (Leach 1993). When filtering particles from the water, mussels are exposed to contaminants that are both in dissolved form and sorbed to particles. The zebra mussel demonstrates high bioconcentration potential for the dissolved contaminants (Fisher *et. al* 1993 , Bruner *et al.* 1994a) due to its relativity high lipid

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content (Bruner *et al.* 1994a). Also, depending on mussel size and the environmental temperature, the uptake rate of dissolved contaminants can vary two fold (Bruner *et al.* 1994a, Gossiaux *et al.* 1996). The particle route of exposure has also been demonstrated using selected PCB congeners (Bruner *et al.* 1994b) with the significance of the route dependent on the bioprocessing mechanisms for particles. Mussels filter most particles in the size range 15-200 μm (Ten Winkel and Davids 1982). However, depending on particle size, composition, and concentration in the water column, a portion of these particles will be ejected as pseudofeces through the inhalant siphon while the remainder are selectively ingested and digested with some residual released as feces.

The objectives of this study were to determine particle clearance rates for two particle types, suspended sediment and algae, measure the rate of pseudofeces production, and determine the assimilation efficiencies of selected polycyclic aromatic hydrocarbon (PAH) congeners and hexachlorobiphenyl (HCBP) sorbed to suspended sediment particles or algae.

## Methods and Materials

### Organisms

Adult zebra mussels were collected from Lake St. Clair (42°20'00" N and 82°47'30" W) at a water depth of 5 m using an epibenthic sled. The collected mussels were cleaned with lake water, placed in a cooler, covered with wet paper towels, and transported to the laboratory. At the laboratory, mussels were transferred to an aerated aquarium filled with Lake Michigan water and maintained at the water temperature measured at the site of collection which ranged from 8 to 15°C. Mussels in culture were fed a daily diet of algae consisting of *Chlorella* granules, (Sun Chlorella Inc. Westbury, NY) and *Chlamydomonus* spp. The *Chlorella* was prepared by adding 3 g of dried algae to 100 mL of distilled water. The slurry was sonicated to break up clumps, and frozen. The frozen cubes were suspended over the aquaria and allowed to melt. The *Chlamydomonus* was prepared in 2000 mL flasks in stock solution using Guillard WC culture medium (Guillard and Lorenzen 1972). This algal culture was allowed to grow for 7 d at 15°C with a photoperiod of 16 h light/8 h dark. The algae were then added to the mussel cultures at a rate of 200 mL of algal solution per day.

Mussel culture water was renewed once a week by replacing one half of the water in the holding tanks with Lake Michigan water at the culture temperature. The culture water was also monitored twice a week for ammonia concentration by the use of ammonia tests kits (Aquarium Pharmaceuticals, INC, Chalfont, PA). Throughout the course of the mussel culturing, the ammonia concentration never exceeded 1 ppm. Furthermore, no mussels were used after being held in culture for more than three weeks.

Mussels used in these studies had a shell length of 15 - 20 mm. The lipid content of 10 individual zebra mussels was determined for each collection of organisms to monitor health. The lipids were measured using a microgravimetric procedure with chloroform/methanol extraction (Gardner *et al.* 1985).

**Chemicals**

The radioisotopes were either purchased from the Sigma Chemical Company (St. Louis, MO) or Chemsyn Science Laboratories (Lenexa, KS) . The compounds included $^{3}$H-pyrene (34 Ci/mMol), $^{3}$H-chrysene (340 mCi/mMol), $^{14}$C-benzo(a)pyrene (BaP, 26.6 mCi/mMol), and $^{14}$C-2,2',4,4',5,5'-hexachlorobiphenyl (HCBP, 17.6 mCi/mMol). All compounds were dissolved in an acetone carrier. The acetone concentration in the exposure water ranged between 0.005 and 0.01 mL/L. The radiopurity was determined by thin layer chromatography (TLC), using hexane:benzene (8:2, v:v) as the solvent. The radiopurity of the radio-labeled compounds was quantified by liquid scintillation counting (LSC). Compound radiopurity was > 98% for all compounds. Analytical procedures were performed under gold fluorescent light ($\lambda$ > 500 nm) to minimize the photodegradation of the PAH congeners.

**Assimilation efficiency studies using suspended sediment**

Assimilation efficiency studies with radiolabeled suspended sediments were performed using sediment collected from Lake Michigan at a 45-m depth off Grand Haven, MI (N43°01.27' W86° 38.05'). The sediment was press-sieved through a 1 mm screen to remove any indigenous species, and 100 g of sediment were added to a 1000 mL graduated cylinder. Filtered Lake Michigan water was added to bring the volume to 1000 mL. The slurry was mixed for 2 min. and allowed to settle for 1 h. The overlying water, 50 mL, was pipetted from the top 100 cm and placed in an Erlenmeyer flask. This resulted in particles that were less than ~5 µm in diameter as calculated from Stokes Law using 2.6 g/mL as the specific gravity of the particles. The particle size range was confirmed using a Coulter Counter (Vanderploeg 1981 a,b). The organic carbon content of a subsample of these particles, was 2.45 ± 0.43 %, (n=5). This was measured on a Perkin-Elmer 2400 CHN elemental analyzer after treating with 1N HCl to remove carbonates. The solution was spiked with $^{3}$H-pyrene and $^{14}$C-BaP and allowed to equilibrate overnight in the dark at 10°C. The solution was then centrifuged at 10,000 g for 15 min. at 10°C. The supernatant was removed, and the remaining material was washed twice with 40 mL of filtered lake water. After the second wash, the particulate material was added to a flask, and the volume was brought to 50 mL with filtered lake water. Aliquots of the solution (4 mL) were then added to 10 beakers containing 200 mL of filtered lake water at 20°C, and initial contaminant concentrations were determined (Table 1).

Table 1. Ranges of contaminant concentrations that were used in assimilation efficiency studies.

| Contaminant | | sediment or algae concentrations (µg /ml water) | Contaminant Concentration (ng /mg sediment or algae) |
|---|---|---|---|
| Pyrene | sediment | 0.27 - 0.46 | 1.59 - 2.59 |
| | algae | 0.18 - 0.95 | 0.74 - 3.99 |
| BaP | sediment | 0.27 - 0.46 | 16.15 - 92.9 |
| | algae | 0.18 - 0.95 | 35.6 - 191.0 |
| Chrysene | algae | 0.93 - 1.62 | 2.90 - 8.90 |
| HCBP | algae | 0.93 - 1.62 | 0.13 - 0.20 |

Prior to the study, the mussels were acclimated to the test temperature of 20°C by increasing the temperature of the culture water by 2°C/day. Once the culture water had assumed the test temperature, the mussels were held for 24 h before testing. Mussels were separated from clumps by cutting the byssal threads with a razor blade. They were placed on a petri dish and those that reattached were presumed healthy and were used in the study. The zebra mussels, 1 per beaker, were added to 6 beakers with the exposure solution and were monitored to determine when filtering began. Filtering was assumed to begin once the inhalant and exhalant siphons were extended. Water samples for contaminant concentration were taken at 1, 2, and 3 h after filtration began. Fifteen mL of 3a70B complete counting cocktail (Research Products International, Mount Prospect, IL) were added to the water samples and then counted on a Packard 2500 TR Liquid Scintillation Analyzer (Meriden, CT) . After 3 h, the mussels were placed in clean filtered water for 1 h. After 3 h of uptake and 1 h of elimination in clean media, pseudofeces were collected by pipette and filtered through tared Whatman GF/C glass microfibre filters. The control and experimental water samples, for times 0 and 3 h, were filtered to recover total particles. The filters were dried in a desiccator, weighed, placed in a scintillation vial with counting cocktail, intensely agitated for 1 min. using a Tekmar 375-watt ultrasonic processor (Tekmar Co., Cincinnati, OH), and counted via LSC to determine particle contaminant concentration. The mussels were analyzed in a similar fashion. Tissue samples were dissected, weighed, and placed in 12 mL of scintillation cocktail. Each tissue was then intensely agitated by sonication for 1 min. Shells were placed in scintillation cocktail without sonication for 24 h and then removed before counting. Assimilation efficiencies were calculated by a particle mass balance approach as follows:

$$Amt_i = (C_p \bullet m_p) - (C_s \bullet m_s) \quad \text{(Eq. 1)}$$

$$Amt_{ss} = Amt_i - (F \bullet m_f) \quad \text{(Eq. 2)}$$

$$\%AE = (Amt_{ss} / Amt_i) \bullet 100 \quad \text{(Eq. 3)}$$

where,

$Amt_f$ = total amount of contaminant filtered (disintegration per minute (DPM))

$C_p$ = concentration of contaminant on particles at the beginning of experiment (DPM/mg)

$m_p$ = mass of particles at the beginning of experiment (mg)

$C_s$ = concentration of contaminant on particles still in suspension at the end of experiment (DPM/mg)

$m_s$ = mass of particles still in suspension at the end of experiment (mg)

$Amt_{ss}$ = amount of contaminant assimilated (DPM)

F = concentration of contaminant in pseudofeces/feces (DPM/mg)

$m_f$ = mass of pseudofeces (mg)

%AE = Assimilation Efficiency

This approach assumes negligible contribution to the contaminant accumulation from the desorption of compound to the water. Further, the 1 h purge is assumed to remove most of the food in the zebra mussel digestive tract.

**Assimilation efficiencies using suspended algae.**

These studies were performed by centrifuging 1000 mL of *Chlamydomonas* cells suspended in culture water. The resulting pellets were then resuspended in 50 mL of lake water. The algal solutions were spiked in contaminant pairs: $^{3}$H-pyrene/$^{14}$C-BaP or $^{3}$H-chrysene/$^{14}$C-HCBP. The spiked solutions were then allowed to sit overnight at 10°C in a darkened environmental chamber. Because the algal mass settled to the bottom of the flask overnight, the overlying water was removed prior to the washing without centrifugation. The three washes, consisting of 40 mL of filtered lake water, were centrifuged at 10,000 g for 10 min at 4°C. After the washes, the volume of the algal solution was adjusted to 50 mL. The algal solution, 4 mL, was added to eight beakers (250 mL) containing 150 mL of filtered water and initial water concentrations of contaminant were determined (Table 1). The remaining procedures were as described above for the suspended sediment assays and the assimilation efficiency was calculated by the mass balance approach.

**Pulse-Chase Algae Study For Examination of Elimination**

A pulse-chase experiment for the algae **AE** study was performed with $^{3}$H-chrysene / $^{14}$C-HCBP using modified methods from Luoma *et al.* (1992). The exposure was performed as previously described except 18 zebra mussels were exposed to the dosed algae. These additional mussels were then used to examine the elimination of the contaminants from their intestinal tracts over time. They were exposed to contaminated algae for three hours then placed in clean, filtered lake water. After 2, 12, 24, 48, 72, and 96 h, three mussels were removed from their individual

beakers, dissected, weighed, and counted on a scintillation counter. During the course of this elimination, the animals were placed into fresh lake water every 24 h and immediately fed 2 mL of concentrated non-radiolabeled *chlamydomonas* sp.

## Results

Filtration Rates

The filtration rates (number of particles filtered per hour) of suspended particles ranged from 3.7 - 7.0 µg/ g tissue/ h for suspended sediment (Table 2) to 0.6 - 8.8 µg/ g tissue/ h for suspended algae (Table 3).

Table 2. Zebra mussel filtration and clearance rates with suspended sediment.

| Aqueous Particle Concentration (mg/L ± S.D.) | Filtration Rate (mg/g tissue/h ± S.D.) | Clearance Rate (ml/g tissue/h ± S.D.) |
|---|---|---|
| 7.4 ± 0.3 | 3.7 ± 1.0 | 493 ± 130 |
| 7.1 ± 0.9 | 4.3 ± 0.9 | 599 ± 126 |
| 5.5 ± 1.2 | 4.9 ± .04 | 897 ± 68 |
| 9.2 ± 0.3 | 7.0 ± 2.0 | 760 ± 201 |

Table 3. Zebra mussel filtration and clearance rates with suspended algae

| Aqueous Algal Concentration (mg/L ± S.D.) | Filtration Rate (mg/g tissue/h ± S.D.) | Clearance Rate (ml/g tissue/h ± S.D.) |
|---|---|---|
| 4.7 ± 0.1 | 0.6 ± 0.4 | 120 ± 78 |
| 25.3 ± 0.5 | 1.5 ± 0.7 | 47 ± 34 |
| 39.2 ± 0.3 | 3.7 ± 1.1 | 94 ± 27 |
| 61.6 ± 3.4 | 8.8 ± 4.0 | 143 ± 66 |

The clearance rates, the amount of water cleared per hour, ranged from 493 to 897 ml/ g tissue/ h for suspended sediment exposures and 47 to 143 ml/ g tissue/ h for suspended algae exposures. Even when the algae and sediment particles were at similar concentrations, the clearance rates for suspended sediment particles were 9 to 10 times greater than for the suspended algae (Tables 2 & 3). An increase of suspended algae concentration, by a factor of 10, did not have any measurable affect on clearance rate (Table 3).

Pseudofeces Production

Measurements of pseudofeces production for sediment and algae were determined at 20°C. Using linear regression analysis, organism size (wet tissue mass, WTM) was negatively correlated with pseudofeces production (PSF) ($p < 0.05$) for sediment. PSF = 13.72(± 1.664) - 0.092 (± 0.019) WTM. $r^2 = 0.54$, n=22. Also, the pseudofeces production was positively correlated with the concentration of sediment in the water (sediment matter concentration, SMC ($p < 0.05$)). PSF = 2.816 (± 0.942)SMC - 10.899 (± 5.717). $r^2 = 0.30$, n=22. Furthermore, pseudofeces production was positively correlated with filtration rates (FILT) ($p < 0.05$). PSF = 0.4774( ± 0.0123)FILT +1.856 (0.567). $r^2 = 0.0244$, n=22.

The pseudofeces production measurements with algae also exhibited a negative relationship between wet tissue mass and pseudofeces production ($p < 0.05$). PSF = 6.005 (± 1.111) - 0.057 (± 0.018) WTM. $r^2 = 0.28$, n = 23. In addition, the pseudofeces production was positively correlated with the concentration of algae in the water (algae matter content, AMC) (Figure 1).

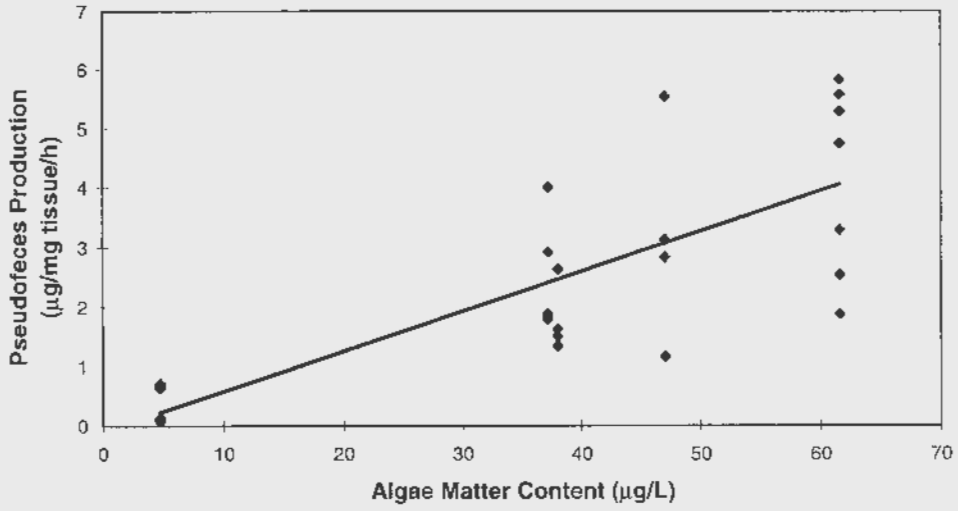


Figure 1. Zebra mussel pseudofeces production rate exhibited a linear relationship with algae matter concentration (AMC). PSF = 0.067 (± 0.013) AMC - 0.092 (± 0.013). $r^2 = 0.52$, n = 23.

The % AE from suspended sediment ranged from 46.1 to 58.3 % (Table 4), using the particle mass balance approach, eq. 1-3.

Table 4. Assimilation efficiencies from zebra mussels using radio-labeled suspended particles.

| Compound | % A E | | Log Kow |
|---|---|---|---|
| | Algae | Sediment | |
| Pyrene | 91.5 (± 2.9)[a] | 58.3 ± (13.5), | 4.88[1] |
| Chrysene | 95.9 (± 2.0)[b] | | 5.79[2] |
| BaP | 91.9 (± 2.2)[a] | 46.1 (± 11.1) | 5.98[2] |
| HCBP | 97.6 (± 0.8)[b] | | 6.90[3] |

Algae n = 8, Sediment n =8 for Pyrene, n =6 for BaP. Compounds with same letter are not significantly different

1 Veith *et al.* (1979), 2 Miller *et al.* (1985), 3 Shiu and Mackay (1986)

Assimilation Efficiencies

The % AE from suspended algae studies ranged from 91.5 to 97.6 % using the particle mass balance approach. Furthermore, there was a positive correlation between % AE and Log $K_{ow}$, % AE = 2.90 Log $K_{ow}$ + 78.0. $r^2 = 0.56$, $p < 0.05$, n=24 (Table 4, BaP data was omitted in calculation). When the algae AE data are fit to a saturation model, eq. 4, quantitative relationships between algae assimilation and Log $K_{ow}$, are observed for all compounds (Figure 2).

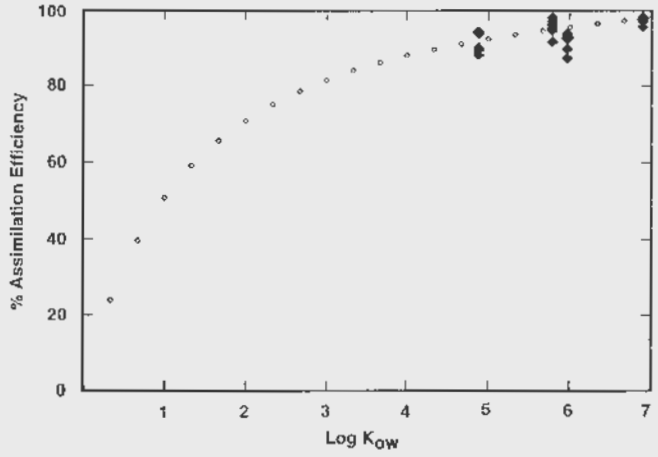


Figure 2. Michaels-Menton type model for determination of maximum Log $K_{ow}$ as % assimilation efficiency approaching 100 % as observed for zebra mussels on suspended algae.

$$AE = \frac{AE_{max}[\log K_{ow}]}{K_m + [LogK_{ow}]} \qquad \text{(Eq. 4)}$$

where AE is the assimilation efficiency and 100% is the maximum AE possible.

For three out of four of the contaminants tested, % AE decreased with an increase in mussel size. However, only HCBP assimilation efficiency exhibited a significant negative relationship with zebra mussel length ($p < 0.05$, % AE = 11072 (± 5.24) - 0.88 (± 0.32) length. $r^2 = 0.44$, n = 12.

## Discussion

### Filtration Rates, Clearance Rates, and Pseudofeces Production:

The laboratory-measured particle clearance rates of the zebra mussels in our study were similar to those found in field studies (Fanslow *et al.* 1995). The observed field clearance rates show that food quality plays a major role in governing clearance rates. An increased concentration of a quality food does not result in an increase in clearance rates. However, zebra mussels, given a low concentration of a poor quality food, exhibit particle clearance rates that are 9 to 10 times higher than those of algal clearance rates (Figure 3).

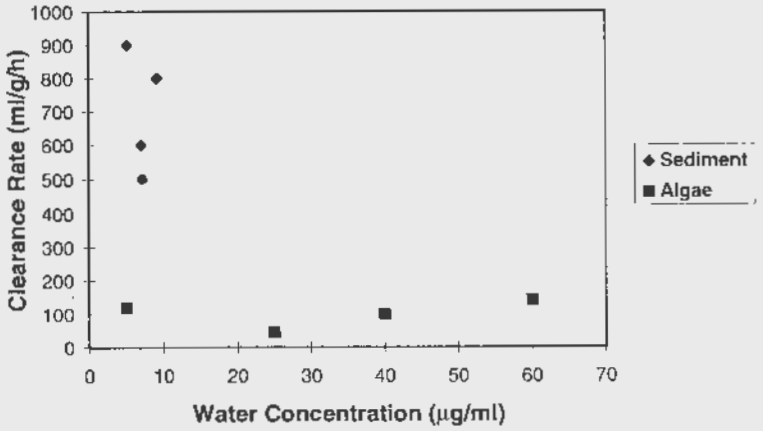


Figure 3. Clearance rates by *Dreissena polymorpha* exposed to mixed water concentrations of suspended sediment and algae solutions. Plotted are the mean values (n=6)

These findings are similar to those of Reeders *et al.* (1989) and Waltz (1978) who showed that suspended matter quality is the most important factor regulating the filtration rate of *Dreissena polymorpha*. Temperature and mussel size are of secondary importance. Thus, exposure to high quality food results in low filtration rates and reduced energy requirements for filtering food.

Zebra mussels that prefer algal particles greater than 5 µm (Sprung and Rose 1988), exhibited a linear relationship between mussel length and algal clearance rates for *Chlamydomonas* cells,10 -16 µm in diameter. The relationship of mussel size and algal clearance appears to be limited by algal size, and no relationship was found with the larger alga *Pandorina*

*morum* (Berg *et al.* 1996). Such relationships between filtering rate and particle size also disappear with small particles as no relationship was found for sediment particles < 5 µm diameter. The absence of a relationship with sediment particles may have occurred, in part, due to the particle composition. That is, sediments are not as preferred a food source as algae. Thus, whether relationships between organism size and particle clearance rates will occur in the field may depend on both the size distribution of the particles and their composition. Because suspended matter in the field often contains more sediment-like solids than algae (Fanslow *et al.* 1995) and predation on algal species is selective (Lavrentyev *et al.* 1995), predictive relationships based on laboratory particle composition may not be appropriate

In our study, a positive linear relation was found between algae matter content with pseudofeces production and a negative linear relation between wet tissue mass with pseudofeces production. Although the measurements of pseudofeces production were determined under laboratory conditions in static studies with water temperature 20°C, algae matter content played a significant role in the pseudofeces production relationship. The decrease in pseudofeces production rate with tissue mass of *D. polymorpha* was also significant ($p < 0.05$) for mussels ranging from 30 - 100 mg. This decrease in pseudofeces production with an increase in tissue mass does not correspond to previously released data. These data sets state that an increase in pseudofeces production was associated with an increase in organism shell length, between 14 and 22 mm (Reeders and Bij de Vaate 1992 and Noordhuis *et al.* 1992). No relationship could be concluded between wet tissue mass and shell length in our studies.

**Assimilation From Sediment:**

The calculations of assimilation efficiency of contaminants were based on the filtration rate, digestion, and absorption of a contaminant. In cases where the PAHs were sorbed to the sediment particles, the assimilation efficiencies were low, generally 42.2 to 58.3%. The sediment particles filtered were < 5 µm in diameter and contained 2.45 % organic carbon. In studies by Kukkonen and Landrum (1995), using sediment from the same source, the < 5 µm fraction of the sediment sorbed 12 - 18 % of the total contaminant dosed to the bulk sediment. Because mussels generally prefer particles in the size range of 15 - 40 µm (Ten Winkel and Davids 1982), the assimilation efficiencies for field sediment might well be different than was observed with this small size fraction. For instance, when the benthic amphipod *Diporeia spp.*, which prefers a particle size range similar to the zebra mussels (Harkey *et al.* 1994), was exposed to dosed sediment from the same site, the AE's of BaP were some what larger and ranged from 45.9 to 60.4 % (Lydy and Landrum 1993, Kukkonen and Landrum 1995).

In a previous study of BaP assimilation, the assimilation from sediment particles by zebra mussels was 20.6 % (± 3.8 S.D.) (Bruner *et al.* 1994b, hereafter referred to as the Bruner study).

Possible reasons for the difference in the measured values between the latter study and this one include: number of mussels in each AE measurement, sediment sources, and experimental design, i.e., mass balance vs. pulse/chase methodology. The Bruner study looked at the assimilation efficiencies for a cluster of mussels rather than single mussels. We noticed that mussels do not always remain open or filter throughout the entire duration of the experiment. Our net calculations considered these fluctuations in filtration while they could have been missed in the Bruner study. If these fluxes are not considered in the net calculations, a lower AE could result.

Differences in the sediment sources and particle size ranges may also have been sources of variation in AE's between the two studies. Lake Michigan sediment was used in this study while Bruner used Olentangy River sediment. Olentangy River sediment had a total organic carbon content of 0.9%, and the sediment fraction < 20 μm was collected by a combination of sieving and settling techniques. The organic carbon content of this fraction is unknown. Thus, there were likely significant differences in the organic carbon concentrations and composition between the two studies.

Another experimental design modification was the utilization of a pulse-chase method for removing and accounting for intestinal content (Bruner *et al.* 1994b). This method in the Bruner study lasted several days, while our studies lasted only 4 h (3 h uptake/ 1 h elimination), except for the last experiment. Despite the shorter elimination time, it appears that 1 h was sufficient to remove unassimilated food particles. From the last phase of this study, which incorporated a 96 h elimination, an ANOVA of the data showed that 1 h was sufficient to remove particles containing HCBP, and there was no significant loss of compound from the tissues for the duration of the elimination phase ($p=0.082$). Chrysene did exhibit an initial loss from the gut over the first 24 h, but this loss was not significantly different from the 2 h time point. Furthermore, an ANOVA revealed that there was no significant loss of compound ($p=0.067$) over the first 52 h of the study. Any further loss of chrysene, from this time forward, is believed to be from tissue residue rather than from expulsion of unassimilated particles. Thus, the experimental design for this study appeared adequate to account for intestinal content. In contrast, the Bruner study found that 24 h was the minimum time needed to clear the gut of unassimilated particles.

A fourth reason for differences between the two studies was the use of different models for the calculation of assimilation efficiency. The Bruner model was a kinetic model that used the contaminant elimination rate determined from previous studies (Bruner *et al.* 1994b, Fisher *et al.* 1993). The elimination rate was not incorporated in our mass balance equations because the time used to purge unassimilated contaminants from the mussel was 1 h, and elimination in that time frame was unimportant. For HCBP, the elimination rate constant is 0.004 /h (Gossiaux *et al.* 1996) and would not have affected the calculation of the contaminant concentration in the mussel tissue with a 1 h elimination phase. However, the elimination rates for relatively water soluble compounds

may need to be incorporated when there is a long period for purging of unassimilated contaminants. This was the case in the Bruner study, which established a 48 h duration for the elimination process.

**Assimilation From Algae:**

The assimilation of contaminants from algae was almost double that from sediment particles. Bruner *et al.* (1994b) observed %AE from algal particles for HCBP of 68.6 (± 2.8 S.D.) % and BaP of 55.6 (± 6.2 S.D.) %, which were significantly lower than those measured in this work (Table 4). However, model design and AE calculation variations may contribute to some of the differences between studies.

Another explanation for differences between this work and that of Bruner may be in the algal lipid content. These variations can be observed during culturing of the algae when nitrogen is in limited supply. In a study of lipid concentrations in algae from the family Chlorophyceace (Mourente *et al.* 1990), *Chlorella* species varied as much as 24 % in their lipid content under varying nitrogen regimes. Gobas *et al.* (1993) observed that the lipid concentration of dietary food influenced the absorption of organochlorine compounds through the process of lymphatic transport in the gastrointestinal tract in fish. His results for the assimilation of HCBP showed a negative relationship between AE and increasing lipid in foods. Though the fish digestion system is different than that of mollusks, the principle of increased fugacity of the compound associated with the food particle as it is digested may be applied. Therefore, *Chlamydomonous* which were higher in lipid content, could have led to lower % AE, and may have contributed to differences between the two studies.

When attempting to determine the relationship between contaminant assimilation and compound characteristics, a limiting maximum AE needs to be recognized. Thus, unlike measuring continuous functions, such as partitioning processes, AE verses compound characteristics should be evaluated via a saturation model. The Michaelis-Menton type saturation model, which defines a quantitative relationship between a saturation process and compound characteristic, was used to determine the relationship of AE to the Log $K_{ow}$. The data from these experiments did fit the predicted model (Figure 2). However, the contaminants chosen had $K_{ow}$ values which were all at the high end of the predicted curve. Whether contaminants with lower Log $K_{ow}$'s would also fit the predicted model is unknown.

**Ecological Significance**

Based on kinetics data and assimilation efficiencies, zebra mussels can readily accumulate PCB and PAH congeners from water and contaminated particles. To determine relative importance

of routes of exposure, a steady-state model was employed to estimate the magnitude of various potential routes during summer and winter, two seasonal extremes.

$$dC_u/dt = k_u C_w + f_h(AE_s f_s C_s E_s + AE_a f_a C_a) \qquad \text{(Eq. 5)}$$

where

$k_u$ = water uptake rate coefficient (mL/g/h).

$C_w$ = relative water concentration (ng/mL)

$f_h$ = filtration rate (mL/g/h).

$AE_s$ = assimilation efficiency of contaminant from sediment particles

$f_s$ = concentration of sediment particles in the water column (gO.C./mL)

$C_s$ = relative contaminant concentrations of sediment particles (ng/mL)

$E_s$ = fraction of ingested material after pseudofeces ejection

$AE_a$ = assimilation efficiency of contaminant from algal particles

$f_a$ = concentration of algal particles in water column (g/mL)

$C_a$ = relative contaminant concentration of algal particles (ng/mL)

Relative concentrations were used since synoptic contaminant concentrations were not available for each potential source. The relative concentrations were based on setting the water concentration at 1 and adjusting the sediment and algae concentrations based on their partition coefficients.

Table 5. Parameters used in steady-state model to determine zebra mussel steady-state HCBP concentrations

| Media | $k_u$ mL/g/h | $C_w$ ng/mL | $f_h$ mL/g/h | $AE_s$ | $f_s$ gOC/mL | $C_s$ ng/gOC | $E_s$ | $AE_a$ | $f_a$ g/mL | $C_a$ ng/g |
|---|---|---|---|---|---|---|---|---|---|---|
| Winter | 564[a] | 1[b] | 1965[c] | .461 | $.48 \cdot 10^{-6}$ [c] | $6.1 \cdot 10^{6}$ [d] | .25 | .98 | $9 \cdot 10^{-8}$ [c] | $1 \cdot 10^{7}$ [b] |
| Summer | 1048[a] | 1[b] | 655[c] | .461 | $1.5 \cdot 10^{-6}$ [c] | $6.1 \cdot 10^{6}$ [d] | .25 | .98 | $1.2 \cdot 10^{-6}$ [c] | $5.6 \cdot 10^{5}$ [b] |

assume temperature of 4°C in winter and 21°C in summer

[a] Fisher et al. (1991)

[b] Relative proportions from BAF values of field collected phytoplankton in Green Bay, Lake Michigan (Swackhamer and Skoglund 1991)

[c] calculations based on chlorophyll concentrations, particulate organic carbon and total suspended solids from 1991 field collections of the inner Saginaw Bay, Lake Huron, Fanslow *et al.* (1995)

[d] calculated from Di Toro *et al.* (1991) $K_{ow}$ and fraction of sediment carbon

Model estimates indicate that algal dietary exposure was the dominate route of exposure at steady state for HCBP for winter conditions (Table 5), (59 % of total contaminant flux). For summer conditions (Table 5), the dissolved HCBP in water was the dominate route of exposure. However, even with the high uptake clearance from water, combined dietary exposure of sediment and algae

even with the high uptake clearance from water, combined dietary exposure of sediment and algae dominated the exposure for both winter (80 % of total contaminant concentration) and summer (52 %). Therefore, additional work to better define the assimilation efficiency and feeding dynamics of the zebra mussel are needed to fully characterize its exposure.

## Conclusion

The algal exposure route was the more important for dietary exposure of zebra mussels to organic contaminants compared to sediment ingestion based on the assimilation efficiency. From model estimates, sediment and algal particles contribute differently to the dietary exposure when comparing summer and winter estimates. Finally, the aqueous dissolved contaminant was the single most important route of exposure in the summer. Better synoptic field measures of algae, sediment and water concentrations are needed to provide realistic estimates of exposure for modeling exercises and to perform environmental risk assessment. Because assimilation efficiencies likely depend on particle characteristics, examination of algae species, size and lipid content and sediment particle characteristics and their impact on contaminant accumulation are required.

## References

Berg, D.J., S.W. Fisher and P.F. Landrum. 1996. Clearance and processing of algal particles by zebra mussels (*Dreissena polymorpha*). J. Great Lakes Res. 22(3):779-788.

Bruner, K.A., S.W. Fisher and P.F. Landrum. 1994a. The role of the zebra mussel, *Dreissena polymorpha*, in contaminant cycling: I. The effect of body size and lipid content on the bioconcentration of PCBs and PAHs. J Great Lakes Res 20(4):725-734.

_____, S.W. Fisher and P.F. Landrum. 1994b. The role of the zebra mussel, *Dreissena polymorpha*, in contaminant cycling. II. Zebra mussel contaminant accumulation from algae and suspended particles, and transfer to the benthic invertebrate, *Gammarus fasciatus*. J. Great Lakes Res. 20(4):735-750.

Di Toro, D. M., C S. Zarba, D.J. Hansen, W.J. Berry, R.C. Swartz, C.E. Cowan, S.P. Pavlou, H.E. Allen, N.A. Thomas, P.R. Paquin. 1991. Technical basis for establishing sediment quality criteria for nonionic organic chemical using equilibrium partitioning. Environmental Toxicology and Chemistry 10:1541-1583

Fanslow, D.L., T.F. Nalepa and G.A. Lang. 1995. Filtration of the zebra mussel (*Dreissena polymorpha*) on natural seston from Saginaw Bay, Lake Huron. J. Great Lakes Res. 21(4): 489-500.

Fisher, S.W., Gossiaux, D.C., Bruner,K.A., and Landrum,P.F. 1993. Investigations of the toxicokinetics of hydrophobic contaminants in the zebra mussel (*Dreissena polymorpha*). In Zebra Mussels: Biology, Impacts and Controls, (eds. T.F. Nalepa and D.W. Schloesser) Lewis Publishes, Ann Arbor, MI. pp 465-490.

Gardner, W.S., W.A, Frez and E.A. Cichocki. 1985. Micromethod for lipids in aquatic invertebrates. Limnol. Oceanogr. 30:1099-1105.

Gobas, F.A.P.C., J.R. McCorquodale and G.D. Haffner. 1993. Intestial absorption and biomagnification of organochlorines. Environmental Toxicology and Chemistry 12:567-576.

Gossiaux, D.C., P.F. Landrum and S.W. Fisher. 1996. Effect of temperature on the accumulation kinetics of PAHs and PCBs in the zebra mussel, *Dreissena polymorpha*. J. Great Lakes Res. 22(2):379-388

Guillard, R.R.L. and C.J. Lorenzen, 1972. Yellow-green algae with chlorphyllide *c*. J. Phycol. 8:10-24.

Harkey, G.A., M.J. Lydy, J. Kukkonen and P.F. Landrum. 1994. Feeding selectivity and assimilation of PAH and PCB in *Diporeia* spp. Environmental Toxicology and Chemistry 13(9):1445-1455.

Kukkonen, J. and P.F. Landrum. 1995. Measuring assimilation efficiencies for sediment-bound PAH and PCB congeners by benthic organisms. Aquatic Toxicology 32:75-92

Lavrentyev, P.J., W.S. Gardner, J.F. Cavaletto and J.R. Beaver. 1995. Effects of the zebra mussel (*Dreissena polymorpha* Pallas) on protozoa and phytoplankton from Saginaw Bay, Lake Huron. J. Great Lakes Res. 21(4):545-557.

Leach, J.H. 1993. Impacts of the zebra mussels (*Dreissena polymorpha*) on water quality and fish spawning reefs in western Lake Erie. In Zebra Mussels: Biology, Impacts and Controls (eds. T.F. Nalepa and D.W. Schloesser) Lewis Publishes, Ann Arbor, MI pp 381-398

Luoma, S.N., C. Johns, N.S. Fisher, N.A. Steinberg, R.S. Oremland, and J.R. Reinfelder. 1992. Determination of selenium bioavailability to a benthic bivalve from particulate and solute pathways. Environ. Sci. Technol. 26:485-491.

Lydy, M.J. and P.F. Landrum. 1993. Assimilation efficiency for sediment-sorbed benzo(a)pyrene by *Diporeia* spp. Aquatic Toxicology 26:209-224.

Miller, M.M., S.P. Wasik, G. Huang, W. Shiu, and D. Mackay. 1985. Relationships between octanol-water partition coefficient and aqueous solubility. Environ. Sci. Technol. 19:522-529.

Mourente, G., L.M. Lubian, and J.M. Odriozola. 1990. Total fatty acid composition as a taxonomic index of some marine microalgae used as food in marine aquaculture. Hydrobiologia 203:147-154.

Noordhuis, R., H.H. Reeders and A. Bij de Vaate. 1992. Filtration rate and pseudofaeces production in zebra mussels and their application in water quality management. Limnologie aktuell Vol 4: 101-114.

O'Neill, C.R. and D.B. MacNeill, 1989. *Dreissena polymorpha*: An unwelcome Great Lakes invader, N.Y. Coop. Extension, Cornell University, NY.

Reeders, H.H., A. Bij de Vaate and F. J. Slim. 1989. The filtration rate of *Dreissena polymorpha* (bivalvia) in three Dutch lakes with references to biological water quality management. Freshwater Biology 22:133 -141.

Reeders, H.H. and A. Bij de Vaate. 1992. Bioprocessing of polluted suspended matter from the water column by the zebra mussel (*Dreissena polymorpha* Pallas). Hydrobiologia 239: 53-63.

Shiu, W.Y. and D. Mackay. 1986. A critical review of aqueous solubilites, vapor pressures, Henry's law constants, and octanol-water partition coefficients of polychlorinated biphenyls. J. Phys. Chem. Ref. Data 15:911-929

Sprung, M., and U. Rose. 1988. Influence of food size and food quality on the feeding of the mussels *Dreissena polymorpha*. Oecologia 77:526-532.

Swackhammer, D.L. and R.S. Skoglund. 1991. The role of phytoplankton in partitioning of hydrophobic organic contaminants in water,. In Organic Substances And Sediments in Water Vol. 2 (eds. R.A. Baker) Lewis Publishes, Cheslea, MI pp 91-105

Ten Winkel, E.H. and C. Davids. 1982. Food selection by *Dreissena Polymorpha* Pallas (Mollusca: Bivalvia). Freshwater Bio 12:553-558.

Vanderploeg, H.A. 1981a. Seasonal particle -size selection by *Diaptomus sicilis* in offshore Lake Michigan. Canadian Journal of Fisheries and Aquatic Sciences. Vol.38 (5):504-517.

_____ 1981b. Effect of the algal length/aperture length ratio on Coulter analyses of lake seston. Canadian Journal of Fisheries and Aquatic Sciences. Vol. 38 (8):912-916.

Veith, G.D., N.M. Austin and R.T. Morris. 1979. A rapid method for estimation of log P for organic chemicals. Water Res. 13:43-47.

Waltz, N. 1978. The energy balance of freshwater mussel *Dreissena polymorpha* Pallas in laboratory experiments and in Lake Constance. I. Pattern of activity, feeding and assimilation efficiency. Arch. Hydrobiol./Suppl. 55:83-105